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MEASUREMENT OF PRECIPITATION BY RADAR

ERKKI JATILA

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1. *Introduction*

The measurement of areal precipitation is the basic problem in those fields of geophysics which deal with the circulation of water in the earth-atmosphere system. A direct application of the measurement of precipitation over an area is the regulation of water courses. Traditionally agriculture is also interested in areal distribution of precipitation. Hydrometeorologists have recently been asked for information about the exact distribution of precipitation by scientists involved with weather modification experiments (see [9], for instance). Today more and more telecommunication systems use centimeter wavelengths. The optimum pattern of the links requires the knowledge of the exact areal distribution of precipitation rates because of attenuation. In near future the three dimensional subsynoptic numerical models will be widely applied. The verification of areal distribution of precipitation will be of great importance for checking the models and improving them.

Conventionally, the areal precipitation is determined by combining the information from several point values measured by rain gauges. These observations contain, however, many errors, depending on the type and location of the gauge [17]. The accuracy of areal rainfall estimates is influenced by the density of the gauge network, type of precipitation, and the climatological as well as topographical characteristics of the area [10]. The rapid data collection also meets with serious problems not easily solved.

During World War II it was found that radar is capable of detecting echoes from rainfall [13]. Some years later MARSHALL *et al.* [14] showed that the echo intensity is a function of rainfall rate. Since that time much work has been done to develop methods for estimating the areal distribution of precipitation by radar (for review articles, see ATLAS [2], KESSLER and WILK [12] or BOROVNIKOV *et al.* [4]).

The purpose of the present thesis is to find a radar method for estimating areal rainfall rates in various types of rainfall and snowfall in Finland. The dissertation consists of the following papers:

- I JÄTILÄ, E., and T. PUHAKKA, 1972: Experiments on the measurement of areal rainfall by radar. *Geophysica*, **12**
- II JÄTILÄ, E., and T. PUHAKKA, 1972: On the accuracy of radar rainfall measurements. *Geophysica*, **12**
- III JÄTILÄ, E., 1972: Experimental study on the measurement of snowfall by radar. *Geophysica*, **12**

Radar measurement were carried out at the University of Helsinki, Department of Meteorology, by the Weather Radar Project headed by the author. The writer was responsible for the basic plans and the organization of the Project.

2. Physical background of radar precipitation measurements

To measure quantitatively the characteristics of a meteorological target which scatters electromagnetic radiation, expressions have been derived between these characteristics and the power scattered by the target. In radar meteorology the most fundamental quantity of the meteorological target is the back scattering cross-section σ , which is defined as »the area intercepting that amount of power which, if scattered isotropically, would return to the receiver an amount of power equal to that actually received» [3]. In practice, when a measurement of scattered power is taken using radar, the average power from a volume (one half of the pulse volume) is received in a moment. If the scatterers are randomly distributed in the volume and mutually independent, the back-scattering cross-sections can be added up, leading to useful quantity, radar reflectivity:

$$\eta = \sum \sigma \quad (1).$$

Radar reflectivity is a quantity related to the power received by the radar. PROBERT-JONES [16] derived an equation between the power received and radar reflectivity:

$$\bar{P}_r = \frac{P_t h G^2 \lambda^2 \Phi \Theta \propto \eta}{1024 \pi^2 r^2 \ln 2} \quad (2),$$

where

- $\bar{P}_r$ = the average power received by radar aerial
- P_t = peak power of a pulse transmitted by radar
- h = length of a pulse
- G = gain of radar aerial
- λ = wavelength

Φ, Θ = beam width to 3 dB points vertically and horizontally, respectively

κ = attenuation factor defined by $10 \log \kappa = 2 \int_0^r (g + c + p) dr$, where g, c , and p are the attenuation (dB/km) caused by gases, cloud, and precipitation, respectively

r = the distance from which the signal is received

The back-scattering cross-section σ of a particle depends on the size and the state of the particle as well as on the wavelength used. Assuming that the particles are small (particle diameter $D < 0.06 \lambda$, [1]), the back-scattering cross-section can be expressed (Rayleigh approximation):

$$\sigma = \frac{\pi^5 |K|^2}{\lambda^4} D^6 \quad (3),$$

where $K = m^2 - 1/m^2 + 2$ with $m = n - in'$, the complex refractive index of the particle. GUNN and EAST [6] gave the values of $|K|^2$ for water and ice. With wavelengths 3–10 cm and at temperatures 0–20°C $|K|^2 = 0.930 \pm 0.004$ for water. For ice particles $|K|^2 = 0.197$.

Combining the equations (1) and (3) the radar reflectivity can be written

$$\eta = \frac{\pi^5 |K|^2}{\lambda^4} \sum D^6 = \frac{\pi^5 |K|^2}{\lambda^4} Z \quad (4),$$

where $Z = \sum D^6$, the s.c. radar reflectivity factor. This equation together with (2) gives the radar equation in the form:

$$\bar{P}_r = \left[\frac{\pi^3}{1024 \ln 2} \right] \left[\frac{P_t h G^2 \Phi \Theta}{\lambda^2} \right] \left[|K|^2 \kappa \frac{Z}{r^2} \right] \quad (5).$$

This expression can be used to calculate the value of Z by measuring the received power $\bar{P}_r$.

The radar reflectivity factor Z is purely a function of particle size distribution. MARSHALL and PALMER [15] demonstrated that for stratiform type rainfall originating as snow, the size distribution can be expressed by

$$N_D = N_0 e^{-\lambda D} \quad (6),$$

where $N_D dD$ is the number of drops of diameter between D and $D + dD$ per unit volume. N_0 is the value of N_D for $D = 0$. MARSHALL

and PALMER [15] gave the value $N_0 = 8000 \text{ m}^{-3} \text{ mm}^{-1}$ for any rainfall intensity.

The parameter Λ depends on rainfall rate and can be written (after Marshall and Palmer):

$$\Lambda = 4.1 R^{-0.21} \text{ mm}^{-1} \quad (7),$$

where R is expressed in mm/h.

When it is considered that the drop size distribution is built of finite size classes, where the diameter of drops is constant, the radar reflectivity factor is written in the form $Z = \sum N_D D^6$. This expression together with the equation (6) gives

$$Z = \int_0^{\infty} N_0 e^{-\Lambda D} D^6 dD \quad (8).$$

If the vertical motion of air is small, the rainfall intensity can be expressed by

$$R = \sum_{D=0}^{D_{\max}} N_D M_D V_D \Lambda D \quad (9),$$

where M_D and V_D are the mass and the terminal velocity of drops belonging to a size interval. The mass and fall speed are functions of drop diameter, and rainfall intensity can be written

$$R = \int_0^{\infty} (N_0 e^{-\Lambda D}) \left(\frac{\pi \rho}{6} D^3 \right) (130 D^{1/2}) dD \quad (10).$$

The last term in parentheses estimates the terminal falling velocity of drops (m/s when D is given in metres) after GUNN and KINZER [7].

By combining the equations (8) and (10) the following $Z - R$ relationship can be derived

$$Z = 1.6 \cdot 10^6 (R^{14/9} / N_0^{5/9}) \quad (11),$$

where the units are for Z $\text{mm}^6 \text{ m}^{-3}$, for R mm h^{-1} , and for N_0 m^{-4} . For further details of the derivation of the equation (11), see KESSLER and WILK [12].

The principals of the derivation of the $Z - R$ relation was presented here to give an idea of the variables which have an effect on the $Z - R$ relationship.

It was assumed that the back-scattering cross-section can be estimated applying the Rayleigh approximation. If, however, the diameter of drops is larger than 0.06λ , the back-scattering cross-section must be calculated from the exact Mie equations. To avoid this complicated procedure, correction factors for larger drops with various wavelengths have been computed to get effective back-scattering cross-sections [6], which can be used to calculate radar reflectivity on the basis of the equation (4). In theory this procedure is quite correct but when reflectivity is being measured by radar, it is impossible to judge the fraction of drops larger than 0.06λ in drop size distribution.

The last statement is valid when the drop size distribution does not follow the Marshall-Palmer law (or some other equation known to describe the size distribution). It has been found that the Marshall-Palmer distribution overestimates the number of drops smaller than 1 mm or larger than 5 mm in diameter. The contribution of these outer parts of the spectrum to the total magnitude of Z (Eq. (8)) is only about 15 per cent after KESSLER and WILK [12]. Thus minor deviations from the Rayleigh approximation have no significance with regard to the accuracy of radar rainfall measurements.

In the derivation of the equation (11) no vertical velocity was allowed. Near the ground this is realistic, but in the heights of radar pulse both the vertical and horizontal speed of air can be considerable. This causes a sorting of particles far from the ideal distribution, resulting a change in the $Z - R$ relationship.

The relationship between the radar reflectivity factor and the rainfall rate expressed by the equation (11) contains a parameter, N_0 , the number of drops with diameter equal to zero. JOSS, THAMS and WALDVOGEL [11] found that N_0 may vary between 300–200 000 $\text{m}^{-3} \text{mm}^{-1}$ from one rain to another. By substituting these values to the equation (11) we find that the $Z - R$ relationship ranges from $Z = 1450 R^{1.56}$ to $Z = 40 R^{1.56}$. Fortunately, they also found that N_0 has a typical value for various type of rainfall (drizzle, stratiform rain, and thunderstorm). MARSHALL and PALMER [15] value $N_0 = 8000 \text{ m}^{-3} \text{mm}^{-1}$ gives a relationship $Z = 234 R^{1.56}$ with the equation (11). Their own locus was $Z = 220 R^{1.60}$, which was later modified into the form

$$Z = 200 R^{1.6} \quad (12).$$

This equation (called the M-P relation in the present paper) has been

widely applied to radar rainfall measurements throughout the world and has given good results for frontal rains [1].

3. *Weather Radar Project at the University of Helsinki*

3.1 The goals of the Project

The first experimental attempts to estimate rainfall intensities using a weather radar were carried out during summer 1968. At this time the goals of the project were formulated for finding answers to the following questions:

1. What is the $Z - R$ relationship in various types of rainfall in Finland?

In studies made mainly in United States [18], United Kingdom [8], and Switzerland [11] different $Z - R$ relationships were found to exist for drizzle, continuous rain and convective showers. However, great differences occur in $Z - R$ relationships for any particular rainfall type obtained in different climatological regions. This is why the $Z - R$ relationship must be determined for various types of precipitation in local conditions. The results are given in Paper I.

2. Which of the known radar measurement methods is the best?

The conversion from measured radar reflectivity factor values to rainfall can be done applying various methods. These are considered in Paper I.

3. What is the accuracy of radar rainfall measurements?

This is a very fundamental question, because the use of weather radar to measure areal distribution of rainfall ought to give far better results than the existing rain gauge network, before the utilization of an expensive technique can be considered feasible. This question is discussed in Paper II.

4. Can radar also be used to estimate snowfall intensities?

Snowfall measurements by radar have previously been carried out in only a few places in the world. Because about 35%—50% of the annual precipitation amount comes in solid form in Finland, the usefulness of radar measurements also in winter time is of great interest. The results of experiments with snowfall measurements are presented in Paper III.

3.2 Equipment and method of measurement used

The radar used in the present studies is Selenia RMT-1L characterized by following parameters:

Wavelength	3.2 cm
Peak power	200 kW
Pulse length	3 μ sec
Pulse repetition frequency	245 pps
Beam width (symmetrical)	1.75°
Effective gain of the aerial	4000

The radar measurements were carried out changing the gain of the receiver at 6 dB steps and filming the scope with each gain value. The measurements of the distribution of scattered power were repeated at five minute intervals. Afterwards, a certain area of the radar scope (the check site in Papers I and II) was picked up and the average rainfall intensity for each measurement time was computed. In Paper III the scattered power was read over special reference gauges; otherwise the radar technique was similar to that used in Papers I and II.

To compare the radar-derived values of rainfall with the »true« observations, a dense network of recording rain gauges was temporarily established (Fig. 1 in Paper I). 15 minute average areal intensities were calculated applying Thiessen's method. These mean areal intensities were then compared with the corresponding radar-measured intensities. The daily amounts of precipitation were also calculated with both methods and the results were compared.

When snowfall was measured by radar, four snow gauges were set up to give reference measurement. The gauges were normal non-recording rain gauges with Nipher shelters. The water equivalent of snow caught by each gauge was obtained by melting the snow in the gauge after each storm. The locations of the gauges are presented in Fig. 1. of Paper III. The sites for the gauges were selected with the greatest possible care to minimize the error due to the wind.

As stated earlier, the power scattered by the particles is a function of the particle size distribution. The drop size distribution measurements were carried out during a number of storms (filter paper technique). Because the drop size distribution varies widely both in time and space the measurements were taken at three places in the check site (Fig. 1 in Paper I). The intention was to take measurements at intervals of

2.5 minutes on each site simultaneously although this requirement was not fulfilled perfectly all the time.

4. Data used

4.1 Rainfall measurements

Areal rainfall was measured over the check site (180 sq.km) during 16 storms, which were classified after the type of rainfall. Table 1. shows the number of storms, duration of rain time, and the total amount of rainfall on the check site and measured by 15 rain gauges for each rainfall type.

Table 1. Data used in rainfall measurements.

Type of rainfall	Number of storms	Duration h	Amount mm
Continuous	8	32.50	34.91
Showers	6	17.25	12.91
Drizzle	2	6.00	11.56
Σ	16	55.75	59.38

4.2 Snowfall measurements

Snowfall amounts were measured at four sites. Measurements were carried out during 9 storms. The duration of storms varied from 1.2 h to 21.3 h. The total measurement time was 67.0 h.

The total snowfall amount (mean value of measurements by all the gauges) was 29.5 mm of water. The daily snowfall amounts ranged between 0.8—9.6 mm of water.

The ground temperature during all the storms was below zero degrees centigrade.

5. Results and discussion

5.1 $Z - R$ relationships for various types of rainfall

Three methods were used for giving daily $Z - R$ relationships:

- 1) calibrating the radar in such a way that the total daily amount of areal precipitation measured by the radar was equal to the total amount of rainfall measured by the network of the gauges. Only

the value of the coefficient a (in the equation $Z = aR^b$) was calculated, while the exponent b was assumed to be a constant equal to 1.6.

- 2) calibrating radar so that the total daily amount of rainfall measured by radar above a fixed reference gauge was equal to the rainfall amount measured by the gauge. Again the exponent b was held as a constant equal to 1.6.
- 3) measuring the drop size distribution in the check site on three places and calculating the average $Z - R$ relation for each storm.

By applying the first method in continuous rains the coefficient a varied between 106 and 402 from storm to storm. In showers the variation was 243—575 and in drizzle 10—68. Weighting the daily value of a by the corresponding areal rainfall amount of each storm the following mean $Z - R$ relationships for various types of rainfall were obtained:

$$\begin{array}{ll} \text{continuous rain: } Z = 196 R^{1.6} \\ \text{showers: } Z = 360 R^{1.6} \\ \text{drizzle: } Z = 56 R^{1.6} \end{array}$$

These are the $Z - R$ relationships recommended by the author to be applied as the first approximation in radar rainfall measurements in Finland or in other districts with a similar climate.

The interstorm variation of the coefficient a utilizing the second method (reference gauge technique) is larger than when applying the first method. In continuous rains a ranges between 84—822 and in showers between 222—2200. The larger variation of a is considered to be caused by the fact that when the radar is calibrated with a larger area (method 1), the spatial variation of drop size distribution is smoothed out. For the second method the mean values of the $Z - R$ relationship weighted by the total amount of areal precipitation of each storm are as follows:

$$\begin{array}{ll} \text{continuous rain: } Z = 191 R^{1.6} \\ \text{showers: } Z = 720 R^{1.6} \\ \text{drizzle: } Z = 28 R^{1.6} \end{array}$$

When the third method (drop size distribution measurements) was applied, both the coefficients a and b were calculated. In continuous rains the value of a was between 185—484 and b between 1.35—1.67 while in showers the corresponding intervals were 201—314 and 1.31—

1.40. Only during one case of drizzle were the drop size distribution measurements carried out giving the values $a = 32$ and $b = 1.28$. The $Z - R$ relationships obtained from drop size distribution measurements are comparable to the ones attained applying the method 1 in continuous rains. In showers, however, the differences are considerable. One reason for this is that the drop size distribution can vary significantly even during a single shower, and the average value calculated from the samples is not representative for the whole check site. Another reason is that larger drops, which may exist in the heights of the radar pulse, can split into smaller drops while falling to the ground. This will cause a decrease in the coefficient a (see Eq. (11), where N_0 increases with the decreasing amount of larger drops).

5.2 Comparison between various radar measurement methods

Areal rainfall amounts measured by radar were calculated by a) applying the $M - P$ relation, b) utilizing reference gauge technique, and c) using the average $Z - R$ relationship obtained from drop size distributions for each storm. The error in total areal radar rainfall amount for all the storms belonging to a certain rainfall type was calculated applying these methods. The mean of the absolute daily errors weighted by the total areal rainfall amount of each storm was also computed. Finally the percentage of »correct» 15 minute radar observations (error less than $\pm 50\%$ in rainfall intensity) was calculated. The results are presented in Table 1.

Table 1. shows that as far as the seasonal or mean daily error in rainfall amount is concerned the best radar method in continuous rains is the utilization of the $M - P$ relation. The second best method is the one using $Z - R$ relationships obtained from drop size measurements. The largest errors in continuous rains were obtained when applying the reference gauge technique.

In showers the reference gauge technique turned out to be the best method. The $M - P$ coefficients systematically overestimated rainfall intensities and the worst radar method was the drop size data method.

In the case of drizzle (only two rains) the $M - P$ coefficients seriously underestimated (50–85 %) rainfall rates. The reference gauge technique succeeded almost perfectly on one day, but overestimated the total areal rainfall amount on another day by 60%. The average drop size distribution was only measured during the other day, leading to an

underestimated (56 %) radar rainfall amount. Due to the small amount of material, it is difficult to judge which of the radar methods used is best in drizzle, but probably the reference gauge technique would considerably improve radar measurements. This assumption is based on the fact that drop size distribution in drizzle does not vary significantly in space and time.

Table 1. Errors (%) in radar rainfall estimates using various measurement methods.

Method of radar measurement	Continuous rains			Showers		
	Error in total seasonal rainfall amount	Mean daily error	Percentage of »correct» 15 min. radar observations	Error in total seasonal rainfall amount	Mean daily error	Percentage of »correct» 15 min. radar observations
M-P	—2.0	11.5	82	42.9	42.9	45
Ref.gauge	13.1	28.9	81	—20.4	25.2	52
Drop size meas.	—11.7	21.2	86	98.2	98.2	28

5.3 The equivalent gauge density of radar measurements

To know how dense a rain gauge network should be in order to give equivalent estimates with radar measurements, the number of gauges in the area (180 sq.km) was altered from 1 to 12. The same errors as given in the previous chapter for the radar measurements were also computed for various network densities. Again it was assumed that the »true» value of areal rainfall was obtained from the recordings of all 15 rain gauges.

Two types of equivalent gauge density (EGD) for radar measurements were defined:

EGD 1: the number of gauges per area leading to a mean error in daily precipitation amount equal to the same error obtained by radar. The mean daily error was calculated as the mean of the absolute percentage daily errors in the precipitation amount weighted by the daily amount of areal rainfall.

EGD 2: the number of gauges per area required to give the same number of »correct» 15 minute observations of areal average rainfall

rate as obtained by radar. A »correct» observation was the one which lay between the error limits of $\pm 50\%$ of the »true» average 15 minute intensity.

EGD 1 describes the ability of radar to measure daily amounts of areal rainfall while EGD 2 shows the accuracy of radar measurements over 15 minutes. Table 2. shows the results.

Table 2. Equivalent gauge density values for various radar methods in continuous and showery rains.

Radar method	Continuous rains		Showers	
	EGD 1	EGD 2	EGD 1	EGD 2
M-P	$\sim 1/180$ sq.km	1/48 sq.km	1/51 sq.km	1/44 sq.km
Ref. gauge	$< 1/180$ sq.km	1/51 sq.km	1/33 sq.km	1/39 sq.km
Drop size meas.	$< 1/180$ sq.km	1/42 sq.km	1/180 sq.km	1/78 sq.km
Mean Z-R relat.	$\sim 1/180$ sq.km	1/47 sq.km	1/26 sq.km	1/33 sq.km

For continuous rains only the M — P coefficient and the mean Z — R relationship ($Z = 196 R^{1.6}$) are equivalent to a gauge density of 1 gauge/180 sq.km, when EGD 1 is considered. In these rains all the radar methods give a value of about 1 gauge/46 sq.km for EGD 2.

In showers the M — P coefficients and the ones obtained from drop size distribution measurements systematically overestimate rainfall rates. Neglecting these methods for this reason, the remaining two radar methods make EGD 1 equal to 1 gauge/30 sq.km and EGD 2 equal to 1 gauge/36 sq.km.

In southern Finland the density of the existing routine rain gauge network is about 1 gauge/500 sq.km. If one wants to measure daily amounts of rainfall in continuous rains as accurately as with radar, the density of the network should be doubled. In showers the number of rain gauges should be about 15 times larger, if the same reliability of daily rainfall amounts is required to be obtained as with radar.

5.4 Measurement of snowfall by radar

The radar measurement of precipitation rates in snowfall is physically based on the same theory as in the case of rainfall. The scattering of electromagnetic radiation by solid hydrometeors is, however, no longer

a simple function of the size distribution of particles. The shape and the structure of the scatterers have their effect on the reflection. If the main crystal type in snowfall is known, one can use various $Z - R$ relationships for each type of snowfall. Unfortunately this is impossible in practice and one must use some average value for the $Z - R$ relation. The best known mean value for aggregate snowflakes is that given by GUNN and MARSHALL [5]: $Z = 2000 R^{2.0}$. This relation was also applied here to snowfall rate measurements by radar. On the other hand, in order to take into account daily variations in $Z - R$ relationships, the reference gauge technique was used.

When the Gunn-Marshall relation was applied to the material, the correlation coefficient of the logarithms of the radar-derived and gauge-measured daily values of the water equivalent of snow was 0.89. The standard error of radar estimates was 0.17, which indicates that about 68 % of radar-derived snowfall amounts fell in the interval -33 % to $+49$ % of the gauge-measured daily amounts of snowfall.

Somewhat better results were obtained when the reference gauge technique was applied. The correlation coefficient was 0.96. For the standard error of estimate a value of 0.12 was obtained, which corresponds the interval -24 % to $+32$ %.

6.11 *Outlook for the future*

The method used to measure the power scattered by rain back to the radar aerial is very simple. As described earlier, the power was estimated changing the gain of the receiver step by step and photographing the PPI-scope at each gain setting. The procedure is laborious and measurement accuracy is poor (3 dB if the interval of successive gain settings is 6 dB). Using this technique only a small fraction of the total information the radar is capable of producing, can be used.

To increase the accuracy of power measurement and to speed up data handling, a processor with a computer-compatible output is necessary. During summer 1972 a signal averager was installed in our radar. It is capable of making an average of 1—512 sequential pulses at 200 range bins. The distance between range bins can be adjusted from a minimum of $2.5 \mu\text{sec}$ (375 m) to any maximum compatible with the radar pulse repetition frequency. The output device is a paper tape punch (110 characters per second). If the average echo signal at each range bin is an output with a 7-bit binary word and only the first 100 range bins

are used, the output time is no more than 1.25 secs. Taking averages at 2 degree intervals in azimuth, the whole 360 degree revolution takes about 4 minutes.

The new processing system operated for about 200 hours during September 1972 so that average echo intensities (64 sequential pulses) were measured at 18000 places within a 150 km radius. The data was collected four times an hour.

The goals of the Radar Project in the near future are to investigate:

- 1) the accuracy of radar measurements up to 200 km
- 2) the influence of the sea (Gulf of Finland) on precipitation patterns
- 3) the influence of orography on precipitation patterns
- 4) the attenuation of electromagnetic radiation in precipitation
- 5) the horizontal and vertical structure of clouds.

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